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Introduction

For historical and logistical reasons, meteorological observations on the Tibetan Plateau (TP) are scarce. It is even more true for mountain-regions, where glaciers have been observed intensively only since recent years. This lack of observations is problematic, regarding their importance for both local and regional ecosystems. Primarily, the Institute of Tibetan Plateau Research (ITP, Chinese Academy of Sciences) is dedicated to current glaciological observations on the TP.

Zhadang Glacier is a small valley glacier (2.48 km^2) located in the Nyainqentanglha Range, about 200 km North from Lhasa (see Fig. 1 and Bolch et al., 2010, for a comprehensive description of the study region and its glacier changes 1976-2009). The glacier is exposed to the northwest and drains into Lake Nam Co (4725 m a.s.l.), Tibet's largest salt water lake. The region is under the complex influence of both the continental climate of Central Asia and the Indian Monsoon system (Kang et al., 2009) what leads to a climate characterised by a strong seasonality in both temperature and precipitation. Only little precipitation occurs during winter, while about 90% of mean annual precipitation is measured from June to September. Glaciers located in this continental summer precipitation climate, with the maximum of annual accumulation and ablation occurring simultaneously, are called summer accumulation type glaciers.

ITP operates two Automatic Weather Stations (AWS) since September 2005 in the area of Zhadang Glacier: one in the accumulation area of the glacier (5785 m a.s.l.) and the other in the valley (5400 m a.s.l.) in front of the glacier. Continuous measurements are supplemented by mass balance measurements applying the glaciological method. The installations have been complemented in May 2009 by Sino-German teams within the DynRG-TiP project [1] with two AWS: one on the ablation zone of the glacier (5660 m a.s.l.) and one that has been relocated recently to the terminal moraine close to the glacier tongue (5550 m a.s.l.). Besides, two time-lapse cameras have been installed in May 2010 (Fig. 1). This makes Zhadang Glacier to be the one of the most sophisticated measurement sites on the TP. Here we focus on the recent DynRG-TiP AWS and camera installations.

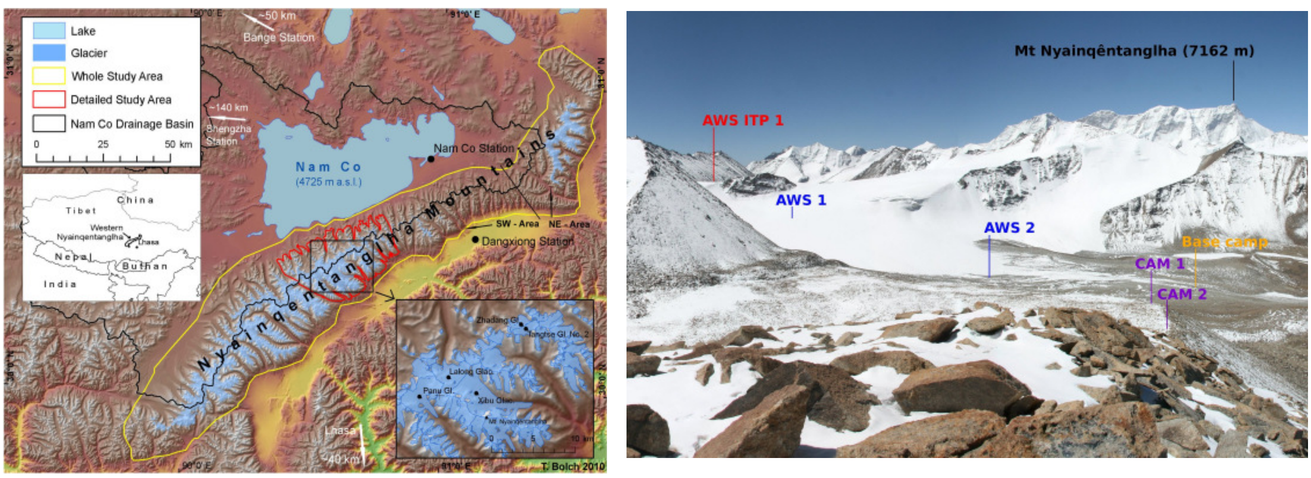

Figure 1. ***Left****: overview of the Nyainqentanglha Range, including a zoom into the Zhadang Glacier area (after Bolch et al., 2010).* ***Right****: Panorama of Zhadang Glacier, with locations of the AWS and camera installations (full panorama available online, [2])*

Logistical aspects

The equipment and mechanical parts have been shipped from Germany to China a few months before our arrival. The Chinese customs allow a temporary import for a period of six months renewable only twice, and ask for a security deposit of about 20% of the ware value. Since our stations operate for a longer period, the deposit has been lost and the ware was officially imported to China in 2010. Some useful mechanical parts (tools, tubes, etc.) can be bought in Lhasa, but they are mostly of inferior quality or heavy.
We usually visit the glacier twice a year (May and September). However, this will no longer be necessary as the systems are now running stable. We expect that one campaign per year towards the end of the ablation season will be sufficient. Due to the high altitude two acclimatisation steps of three days each are necessary (Lhasa, 3650 m a.s.l. and Nam Co, 4740 m a.s.l) before being capable to go up to the base camp (5400 m a.s.l.), which is reached in a one day walk. Tibetan nomads are living in the valley from May to September and let their yaks graze. Without their support and the strength of their horses or yaks to carry our equipment, the ascension would be virtually impossible. However, the nomads are not always in favour of our activities: some of them are superstitious and recently our stations were held responsible for various capricious weather phenomena.

Automatic weather stations

The instruments (Table 1) were primarily mounted on a mast drilled into the ice to more than 2.5 m depth. Based on the mass balance measurements in previous years (about 1 m w.e. per year, Kang et al., 2009) and our own estimation of the equilibrium line altitude, this seemed to be a reasonable choice. The high ablation in 2009, estimated to 2,5 m of ice, caused the fall of both stations around mid-July. Therefore, we changed to a tripod set-up and a separate mast for the sonic ranger (Campbell SR50) (Fig. 2). The stations was supposed to stay on their feet as the ice level decreases but for some reasons (extreme wind? debris within the ice?) the stations again fell over in summer 2010. ITP staff could re-erect them one month later. A construction with wider feet extent may have been more stable, but difficult to find in China. The SR50 structure inspired by Oerlemans et al., 2004 (three tubes of 5 m length, drilled inclined into the ice) proved to be very stable, but the inclined holes are difficult to drill properly using the steam drill.

Table 1. *Specifications for the AWS instruments*

Measured quantity	Instrument	Sample interval
Air temperature (2 heights)	CS215 (Campbell)	10 min
Relative humidity (2 heights)	CS215 (Campbell)	10 min
Air pressure	DPI740 (T. Friedrichs & Co)	10 min
Net radiation	NR-Lite (Campbell)	10 min
Solar radiation (up and down)	CS300 (Campbell)	10 min
Longwave radiation (up)	IRTS-P (Apogee)	10 min
Ice temperature (8 depths, down to 9 m)	107TP (Campbell)	10 min
Surface height	SR50 (Campbell)	10 min
Wind speed and direction	05103 (Young)	10 sec sample, 10 min storage
Wind (sonic anemometer)	WindMaster (Gill)	10 Hz sample, 10 min storage
Mast inclination (2D)	SCA121T (VTI Tech.)	10 min

Figure 2. ***Left:*** *The AWS 1 in autumn 2010 and our young Tibetan helper.* ***Right:*** *The terrestrial camera system (placed in a waterproof box that is closed afterwards)*

The stations worked perfectly and had no data or power failures (radiation values are high also in winter and the batteries are recharged efficiently). Thanks to the inclinometer placed at the mast, it was easy to track all events of falling over. By this means valid measurement periods could be selected. The low-cost of the sensor is less of a problem than the provision of two extra slots on the data-logger (CR1000, Campbell). Nevertheless, this is really worthwhile considering the importance of the information on mast tilt. In order to measure the radiation budget we replaced the popular CNR1 from Kipp & Zonen by the cost-effective 4-sensor installation described in Table 1. The shortwave radiation measurements proved to be accurate. In contrast, the longwave radiation measurements were not satisfying for two reasons. The IRTS sensor shows high sensitivity to solar radiation and measured snow surface temperatures up to several K above the melting point during the day. Furthermore, incoming longwave radiation (obtained using the net radiation value subtracted from the three measured components) suffers from accuracy problems due to the different frequency responses of the various sensors. Two temperature and relative humidity (RH) probes are placed in a ventilated radiation shield (THIES Clima GmbH). The ventilators are directly connected to two solar panels in an independent circuit. This has the strong advantage that the ventilator will not use the power of the battery and that the probes are efficiently ventilated during the day. However, there is the disadvantage that the probes are not ventilated at night. The solar panel voltage is sampled every 10 minutes to track the strength of ventilation. The effect of this ventilation strategy in comparison with permanent ventilation needs to be evaluated in more detail.

Terrestrial cameras

We installed two cameras on the glacier lateral moraine (Canon EOS D-60, objective of 28 mm focus, fixed aperture value of 7.1 and adaptive aperture time) taking three (recently changed to six) pictures a day of the glacier tongue area. The power supply for each camera and the camera timer, responsible for the triggering impulse, is ensured by a single 12V battery recharged by a solar panel. Because both cameras (base of about 400 m with a base-to-height ratio of about 0.3) are operating simultaneously it is possible to compute glacier volume changes using stereoscopy. Therefore, 14 Ground Control Points (GCPs) were measured in the glacier forefield. As point locations we chose single boulders which are supposed to be stable over time.
Even though one of the cameras was stolen in summer 2010, the second camera provided a dataset of high quality (animation available online, [3]). The pictures allow a rare insight into the meteorological and surface conditions of the glacier on a sub-daily basis, which is useful for AWS data processing, analysis and validation. For example, the image time series was analysed in order to produce a dataset of the timing and intensity of snow events which was used for the validation of the sonic ranger snowfall algorithm.

Data treatment

During winter, the tripod feet are covered by ice and snow and the system is very stable. Only standard corrections are necessary (RH for temperatures below zero using the values given by Campbell, interpolation of temperature and humidity at the 2 m height, sonic range correction for temperature). During summer, rapid snow events and follow-up melt may occur within hours. High wind speeds and surface changes make the station stagger.

Precipitation often occurs in the form of soft hail. All these surface conditions together seem to influence the quality of the signal of the sonic ranger. The quality flag provided by the sensor is useful for automatically filtering a large part of the invalid data. Nevertheless, the signal remains noisy (sometimes above the accuracy of 1 cm specified by the manufacturer) especially during precipitation events. The temperature correction is necessary to avoid artefacts, as the measured distance may "diminish" at the end of the day. This could falsely be interpreted as a snow event. In order to minimise this effect, a 3 h moving mean of top and bottom temperature sensors was used for the correction. Finally, a 3 h moving mean is applied to the sonic ranger data for noise reduction. A larger window size would increase the smoothing but would reduce the signal of the short and small (less than 10 cm) but frequent snow events of the summer season.

For the detection and quantification of snow events using sonic ranger data, several algorithms were compared and gave largely variable results (up to a factor 3 in the amounts). The main issue is that no validation can be made without a reference dataset. Using the information provided by the time-lapse camera as reference, one of the algorithms could objectively be selected. The 6 hourly snowfall amount is obtained as follows: if the mean surface height (snow depth) of the 6 h period is higher of at least 1 cm than the mean surface height of the previous 6 h, then a snow event occurred. The 6 h snowfall is given by the difference between the maximum and the minimum surface height during these 6 h.

Recommendations and conclusions

In this document, we presented the operation of two AWS and two cameras in the harsh environment of the TP. We addressed several topics such as logistics, instrumentation, mechanical construction and data treatment. In general, our field experiment is a success, but we also made several mistakes that we would like to share in the following list of recommendations. They are based on our own experience, and may be not entirely new or even be unsuitable for other environments.

- Despite the high altitude, ablation is very strong on glaciers of the central TP. The ablation season is short (June to mid-August) but intense. Therefore, AWS constructions based on stable tripods are recommended for altitude ranges below 6000 m a.s.l.
- The tripod should be as light and as bright as possible to resist the harsh weather conditions.
- A second system, installed next to the glacier, emerged as the safest way to ensure continuous data collection.
- Time-lapse cameras, besides the application for stereoscopy, are a useful tool to understand and observe surface and near-surface conditions of a glacier. Cost-effective systems are easily available for such purposes.
- The "daytime ventilation", radiation shield ventilators directly connected to independent dedicated solar panels, is an efficient way to ensure the power supply of the instruments. The effect of this ventilation strategy on the temperature measurements especially during night is not yet quantified.
- If there are adequate financial resources, a direct measurement of all four radiation components using accurate sensors is a good solution to avoid complex and imperfect data post-processing.
- If there are enough slots available on the data-logger, the measurement of the tilt of the mast simplifies many aspects of data post-processing.
- The signal quality flag provided by the SR50 sensor provides useful information for efficient data filtering. There should be a memory slot reserved on the data logger for this number if ever possible.

The authors will be pleased to answer any further questions and are open to suggestions or comments regarding this list.

In the meantime, the efforts of measuring near surface meteorology on Zhadang Glacier have provided us with outstanding and unique data (see Fig. 3) that in the near future will allow accurate and state-of-the-art investigation of surface energy and mass exchange from a logistically difficult remote high altitude site.

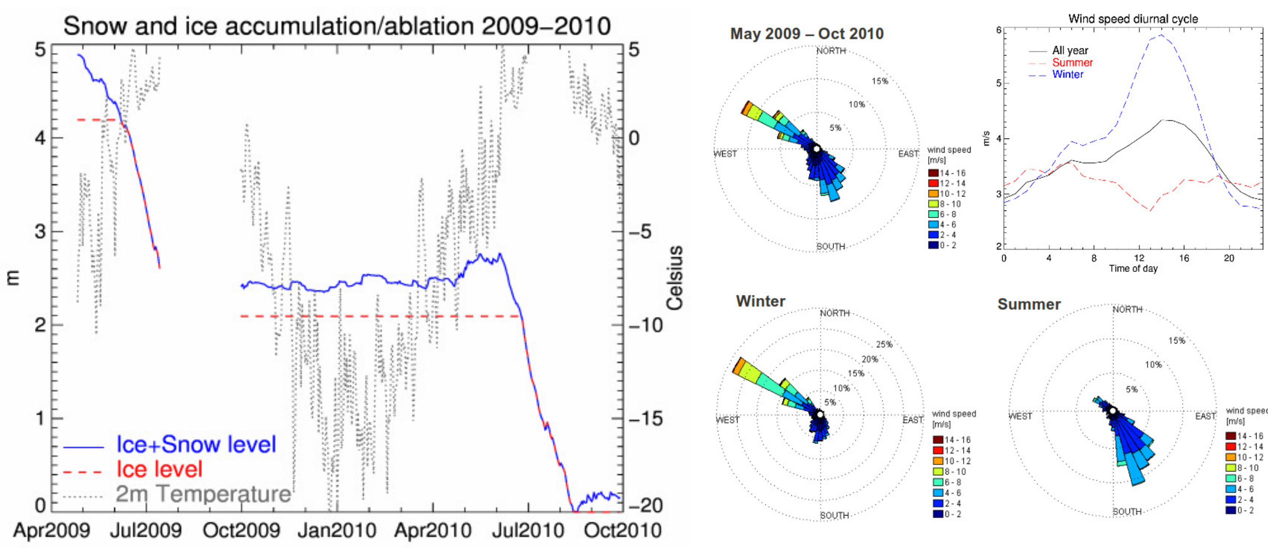

Figure 3. ***Left:*** *Daily means of snow accumulation and ablation at AWS 1 in 2009 and 2010 and air temperature.* ***Right:*** *Wind roses and diurnal cycle of wind speed for the whole measurement period, winter season and summer season.*

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[2] Panorama: http://www.klima.tu-berlin.de/forschung/Asien/tibet/pics/panorama/zhadang_pano.html.

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